EMC ISSUES OF ELECTRIC DRIVES IN AUTOMOTIVE APPLICATIONS

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Abstract: From the EMC point of view, the integration of electric drive systems into today's cars represents a substantial challenge. The electric drive system is a new component consisting of a high-voltage power source, a frequency converter, an electric motor and shielded or unshielded high-power cables. Treating this new electric drive system or its components as a conventional automotive component in terms of EMI test procedures and emission limits would lead to substantial incompatibility problems. In this paper the EMC issues related to the integration of an electric drive system into a conventional passenger car are investigated. The components of the drive system have been analyzed being either noise sources or part of the coupling path within the new electrical system of the car. The obtained results can also be used to determine the acceptable noise levels on a high voltage bus of an electric drive system.

Introduction

From the EMC point of view, the integration of electric drive systems into today's cars represents a substantial challenge. Due to the strict EMC requirements within the automotive environment, resonant converter topologies or even multilevel inverters have been explored to be advantageous for electric vehicle drives [1-3]. However, the first commercial applications are equipped with a conventional hard switching power converter that will be discussed in this paper.

The future drive concepts for passenger cars include an electric drive system either to reduce the fuel consumption or to build up a zero-emission vehicle. Possible solutions are the hybrid car, the pure electric car and the fuel cell car. Figure 1 shows the configurations for the electric systems that are implemented in those cars [4].

Although the ideas for the power supply differ in each of these cases, the drive concepts are very similar from the viewpoint of Electromagnetic Compatibility (EMC). Yet they differ extremely from conventional automotive electrical system components.

The power required by the electric drive is much higher than the power demand of the whole electric system in today´s conventional cars. The voltage in the high-voltage bus can be as high as 900 V. Therefore, conventional test procedures are not appropriate for such components due to size, weight, power and emitted noise.

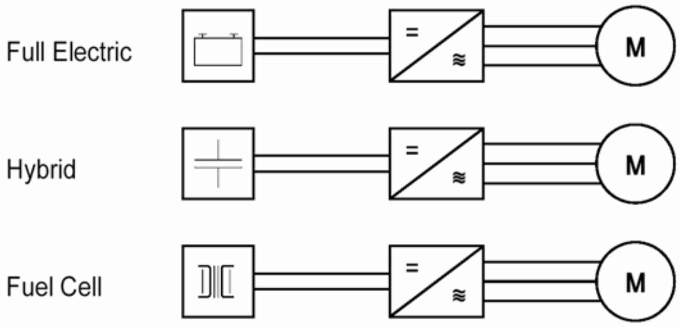

Figure 1: Electric Drive System Configurations for Passenger Cars

On the other hand, as a first approximation the components can be considered to be not connected to the car's conventional electrical system by lines. The electric drive components are running on the HV-Bus which is made as a completely insulated power supply network. Moreover, the cables of the HV-Bus are often shielded. However, existing EMC requirements for conventional electrical system components do not take the shielding of cables into account [5]. Treating this new electric drive system or its components as a conventional automotive component in terms of EMC test procedures would lead to substantial incompatibility problems. Additionally, the effort for filtering would be unreasonable high.

Therefore, a new approach has to be developed in order to find appropriate emission limits for the electric drive components. These limits have to take the specific of the new components and the new drive system into account. They also have to be strict enough to ensure the electromagnetic compatibility of the

whole system. Furthermore, with this approach, we have to deal with the connections between both the conventional and the new electric drive system [6].
In this paper such an approach is described consisting of

1. an analysis of the new electric drive system in order to be able to predict the noise emitted within the system,

2. a determination of the coupling paths existing between the new electrical drive components and the conventional electrical system,

3. an adaptation of the EMC requirements of the conventional electrical system to the new electrical drive components using the coupling models.

Exemplarily shown in this paper, a new approach makes it possible to specify maximum interference levels on the high voltage bus. The knowledge available about modeling power electronic systems to be a noise source is adapted to answer the question how much noise is acceptable within a certain electrical environment [7].

EMC Behavior of the electric Drive

The main components of the new electric drive for automotive applications are the electric motor, the power converter, the power supply and the lines connecting the components. Each of these components acts as a path for electromagnetic emissions. The power converter is known to be the main source of EMI. So the components of the drive system have to be analyzed being either noise source or part of the coupling path within the car's new electrical system.

Power Converters

Power electronic systems are known to be the main source of electromagnetic interferences within electric drive systems. The high speed switching device, e.g. the insulated gate bipolar transistors (IGBT), is the noise source which has to be modeled. A method to calculate the generated EMI of power electronic devices with changing pulse patterns is introduced in [8]. Most available physics-based models of semiconductor switches are not developed for high frequency calculations. For this reason, a simplified description of the noise source is derived.

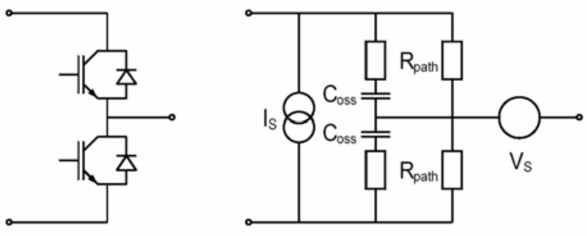

Figure 2: Half Bridge and its Equivalent Circuit to Predict EMI

Figure 2 shows the equivalent circuit to predict EMI of a high power density inverter. The current source I_S models the current flowing into the half bridge. This current represents the source of differential mode interferences. The task of the voltage source V_S is to model the output voltage which is the source of common mode interferences. Validity of these simplifications is proven in [8], thus the results can be used for further investigations.

Electric Motor

Another crucial factor for an accurate EMI analysis and prediction is the representation of the electric motor in the EMI frequency range. The way noise currents flow inside the machine does not necessarily have to be determined. In fact, it is more important to understand the impedance of the electric motor as a part of the noise path and to know how this impedance varies as a function of frequency.
For several years now, research has been done on the electric motor and its impedance considering electromagnetic noise in power electronic systems. The high-frequency representation of the motor impedance depends on the electric motor principle and not on the drive application. Since the electric motors used in electric vehicles are common ac machines, the high-frequency representations developed for other applications than electric drives can be used for EMI predictions in electric vehicles.

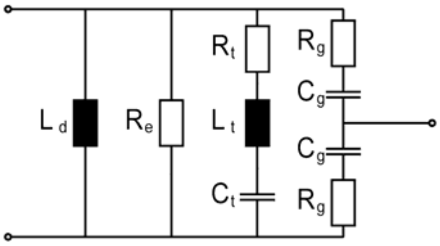

Figure 3: Per-phase Representation of the AC Motor

Figure 3 shows a high-frequency per-phase representation of an ac motor that has been proposed for over-voltage analysis by Moreira. The parameter C_g represents the winding-to-ground capacitance. The parameter R_g is added in the circuit to represent the dissipative effects that exist in the motor frame resistance. The circuit formed by the parameters R_t, L_t and C_t is related to the winding turn-to-turn capacitance. The parameter R_e is responsible to account for the losses introduced by eddy current inside the magnetic core. The parameter L_d represents the leakage inductance of the machine winding. The methodology for the parameter estimation can be found in [9].

Traction Battery

The battery providing power for the converter is a main part of the path for EMI. Therefore, the battery behavior within the high frequency range needs to be determined. Since no appropriate model for traction batteries has been found in the literature, the model developed for this project is explained more detailed here.

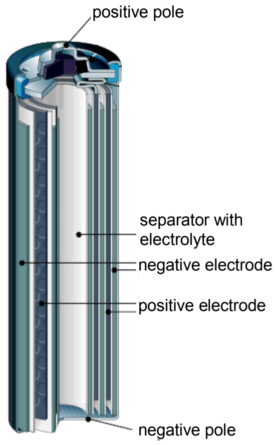

Figure 4: Structure of Cylindrical NiMH Battery

The basic structure of a battery consists of two electrodes and an electrolyte embedded in a mechanical separator. In cylindrical batteries the electrodes are rolled (Figure 4), while they are laminated in prismatic batteries. The RF-properties result from the current path through this structure. Figure 5 demonstrates the current flow for two electrodes via the electrolyte.
Hoene has presented a new approach to model the battery regarding its dense packaging of electrodes and the direction of the current flow as a solid conductor [10].

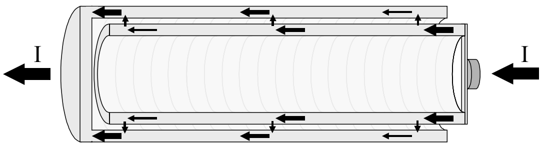

Figure 5: Current Path through Battery

By using a homogeneous material instead of the electrode structure, properties like the internal and the external inductance or the skin effect can be predicted easily. Then the material properties of the homogeneous conductor have to emulate the material mix of electrodes and electrolyte.
Figure 6 shows the behavior model for a single battery cell in the EMC frequency range. The model is parameterized and proved by impedance measurements on battery cells.

The model consists of the internal inductance and resistance (L_{int} and R_{int}), which both depend on the frequency due to the skin effect. Furthermore, the external inductance is represented by L_{ex}; the resistance of contacts by R_c. C_e models the capacitance between the electrodes and R_{ch} and V_{ch} which give a simplified description of the chemical processes. If necessary, they can be replaced by a more detailed low frequency model.

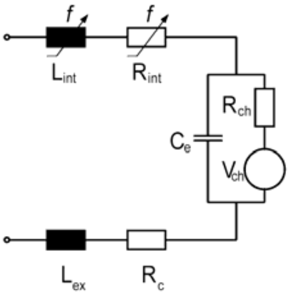

Figure 6: Equivalent Circuit to Model Rf-Characteristics of Batteries in Regarded Frequency Range

The internal DC resistance is given by the cross section A and the length l of the battery and the conductivity σ_{eff} of the homogeneous equivalent material (all in SI units).

$$R_{\text{int},DC} = \frac{l}{\sigma_{eff} * A} \quad [\Omega] \tag{1}$$

To calculate the frequency dependent resistance, the skin effect formula for round conductors is used where f is the frequency, μ_0 the absolute permeability, $\mu_{r,eff}$ the relative permeability of the homogenous equivalent material and r the radius of the battery.

$$R_{\text{int},Skin} = \sqrt{\frac{f * \mu_0 * \mu_{r,eff}}{4\pi * r^2 * \sigma_{eff}}} * 1 \quad [\Omega] \tag{2}$$

A correction factor is added for prismatic batteries to take the influence of the battery's shape into account. The formulas for low and high frequency behavior are joined by a formula which is not physically but empirically proven:

$$R_{\text{int}} = \sqrt{R_{\text{int},DC}{}^2 + R_{\text{int},Skin}{}^2} \quad [\Omega] \tag{3}$$

The internal inductance for round conductors is divided into a DC (4) and a frequency dependent part (5).

$$L_{\text{int},DC} = \frac{\mu_0 \mu_{r,eff}}{8 * \pi} * 1 \quad [\text{H}] \tag{4}$$

$$L_{\text{int},HF} = \sqrt{\frac{\mu_0 * \mu_{r,eff}}{16 * \pi^3 * r^2 * \sigma_{eff} * f}} * 1 \quad [\text{H}] \tag{5}$$

The total internal inductance is calculated by (6).

$$L_{\text{int}} = \frac{1}{\sqrt{\frac{1}{L_{\text{int},DC}{}^2} + \frac{1}{L_{\text{int},Skin}{}^2}}} \quad [\text{H}] \tag{6}$$

The external magnetic field strongly depends on the shape and the distance of the return path of the current. In [11], formulas are given to calculate the inductance for standard geometries of conductors. Regarding the batteries as solid conductors, these formulas can be applied to the geometry implemented in a specific battery. The contact resistance RC is also parameterized according to the specific setup.

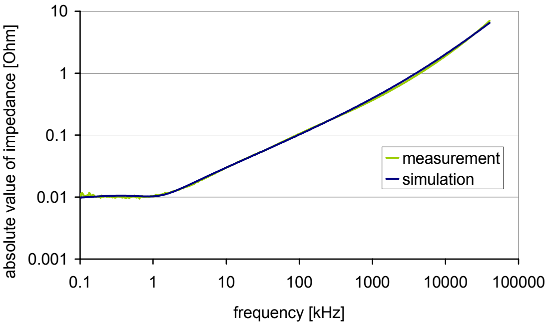

Figure 7: Absolute Value of Battery Impedance

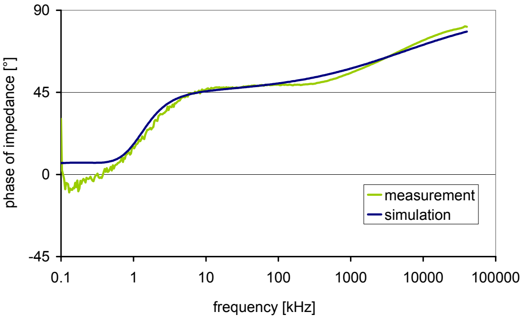

Figure 8: Phase of Battery Impedance

shows the measured and simulated absolute value of the impedance of a cylindrical NiMH-Cell with 3.3 cm diameter and 37 cm length, while shows the measured and simulated phase. The simulations match the measured data and therefore validate the proposed simplifications. Hence, the description of the traction battery as a part of the noise path is appropriate for EMI prediction and advanced mitigation development.

Power Cables

The cables of the high-voltage bus connecting the power converter with the motor and the power supply have to be taken into account to describe the new electric drive system.

Due to the ratio between the size of the power converter and the frequency of the EMI, power electronic applications emit the noise mainly through their lines. That's why the cables for the high-voltage bus are so important during the design process of an electrically driven vehicle.

Usually the connection between converter and motor is kept very short to gain better results in terms of volume and EMC. Restrictions regarding the space available within the car demand cables for the connection to the power supply. From the EMC point of view, there are high-voltage lines within the system carrying the supply voltage as high as 900 V.

The main question during the design process is to find out if shielded cables are necessary or not. In general, shielding can reduce the mitigations to ensure EMC within the system, but drawbacks are higher costs and reduced flexibility, the latter causing problems for the assembling. Regarding EMC criteria, the best solution would be a common shielding of both high-voltage bus lines. Such a solution would even aggravate the problem since the cooling conditions deteriorate, and therefore the size of the cable has to increase. In turn, that means higher costs and lower flexibility.

For the work presented here, shielded power cables with 70 mm^2 cross section especially designed for an electric drive have been used. The shielded cables are modeled by the lumped parameter line element model shown in Figure 9. It consists of the inductance L_C for the inner conductor, L_S for the inductance of the shield and the mutual inductance M_{CS} between both. They are calculated from geometrical dimensions with analytical formulas found in the literature [11, 13] as well as the capacitance C_S between the cable shield and the ground plane. Resistances of the shield and the inner conductor RS and R_C depend on the frequency due to the skin effect, which influences the shielding effect and the damping at resonance frequencies. Frequency dependent effects like diffusion and dielectric losses are of outstanding importance for the correct simulation of resonances in the coupling paths. [14]

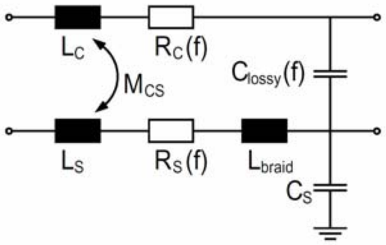

Figure 9: One of Ten Line Elements Modeling Power Cable

That's why the described model is only suited for simulations in the frequency domain. An additional inductor L_{braid} on the braided shield which is not coupled to any other inductors, represents abating shielding effectiveness due to inductivity of the braid and its holes. The investigated cable is 1.5 m long according to the setups defined in [5]. Its isolator shows a relative dielectric constant around εr = 4. As the model has to be valid up to 100 MHz, where a wavelength of approximately 1.5 m appears, ten line elements of length less 10 are used. Figure 10 shows the impedance of one high-voltage cable. The impedance calculated without dielectric losses differs clearly from measured values. Due to the fact that coupling and radiation of EMI from shielded cables is a problem mainly at occurring resonance frequencies, efforts are made to model dielectric losses correctly. This is particularly of importance for absolute values at resonance frequencies. The highest resonance frequencies of the power cable are also not correctly calculated if the decrease of the cable's capacitance with the frequency is not considered.

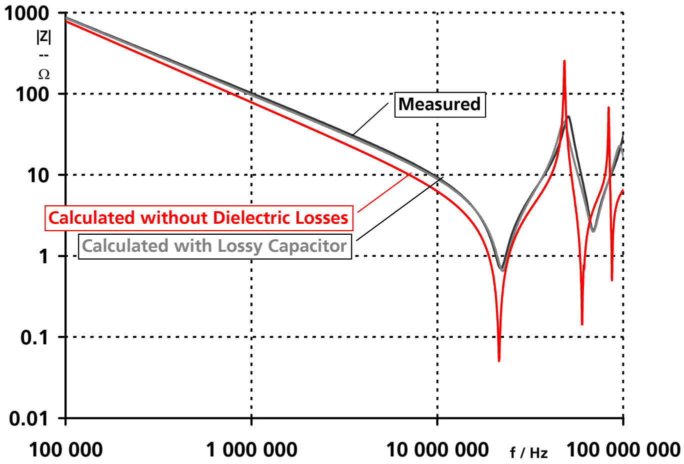

Figure 10: Impedance of Shielded Power Cable of 1.5 m Length

The trade-off between shielded cables and EMI mitigations can only be found for specific applications. As presented in this paper, research can provide guidelines for the necessary decisions.

Coupling Paths

The new electric drive system consists of several components which are mainly connected to the new high-voltage bus only. Integrating the new electric drive system into a vehicle, the noise sink to be protected against interference is the conventional electric system and its low-voltage devices such as the radio receiver. Existing requirements such as those for EMC aim to the compatibility within the conventional electrical system. In order to ensure compatibility within the new system, the connections between the conventional system and the new components have to be analyzed. Although the high-voltage system will be insulated and won't use the car body as return conductor like the low-voltage supply system does, indented and unintended connections will have to be taken into account. As shown in Figure 11, three different coupling paths have to be considered.

1. DC / DC – Converter connecting low and high voltage bus
2. Control and low Power Supply for the Power Converter
3. Crosstalk between the parallel lines.

The DC / DC converter connects the low voltage system and the high voltage system in order to provide electrical energy to the low voltage system. Therefore, an additional power generator for the low voltage system can be avoided. From the viewpoint of EMC this forms a noise path due to the parasitic elements of the DC / DC converter itself.

The power converter does not work on its own. In order to ensure a save operation, many sensing lines as well as an additional low voltage power supply connect the power converter to the low voltage system. Although this forms a noise path that has the ability to ruin a whole EMC concept, it could not be taken into account for this project. The parasitic paths within a power converter strongly depend on the special application. General results cannot be obtained by investigating one specific power converter in its specific arrangement.

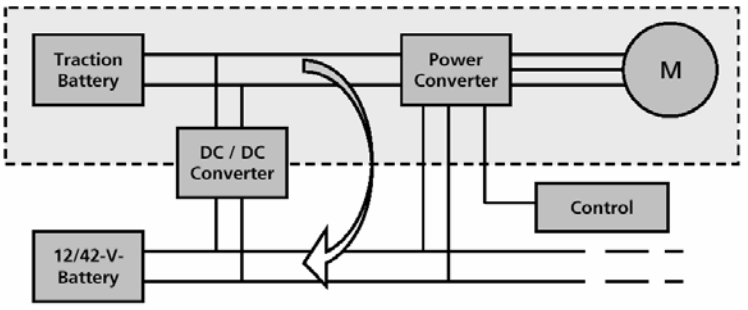

Figure 11: Coupling within Electric Systems

As space for wiring harness is limited in modern cars, high-voltage and low-voltage cables are arranged closely to each other. Hence one important coupling path is crosstalk between the different lines.
Besides crosstalk, the EMI radiated from the high-voltage cables into the vehicle is an issue to be addressed to. EMI radiated from the high-voltage bus has to fulfill the same standards as any other line connecting low-voltage components. As the conventional procedures can be used for EMC assessment of the high-voltage bus without changes, this will not be stressed any further in this paper..
From the different coupling paths introduced here the coupling due to crosstalk and the coupling through the DC / DC converter are both suitable for an investigation in a research project.

Crosstalk Modeling

For quantifying crosstalk, the underlying idea is to place the cables of the high power bus close to the cables of the low power bus.

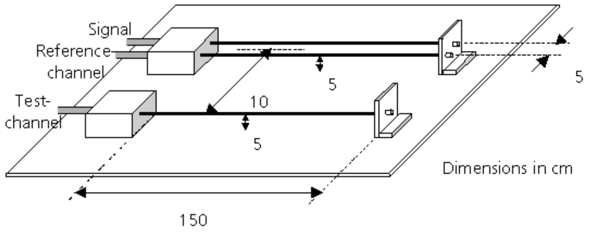

Figure 12: Layout for Inductive Coupling Modeling

The setup is derived from the setup required for the conducted emission measurements according to the SAE standards. The high-voltage bus cables – possibly shielded – are arranged in parallel to one line representing the low-voltage bus or any sensible signal line. The low-voltage line is connected to a line stabilizing network (LISN) on one side and to a component with worst-case impedance on the other side. Impedance of the component's input terminal is supposed to be small for worst-case inspection. Values for worst-case inspection are mentioned in [12]. In case of signal lines input terminal impedance is highly ohmic, at least 100 Ω. Power input terminals are less ohmic, at least 0.1 Ω. Based on this setup the impact of an electric drive system on the low-voltage electrical system of a passenger car can be quantified by measurement or simulation with lumped parameter models.
As test setup two shielded cables with 70 mm^2 cross section of the inner conductor are chosen and assembled on a conducting ground plane as shown in Figure 12. In order to determine crosstalk, an inphase test signal is injected into both cables by a Gain-Phase Analyzer (HP4194A). The resulting signal is measured on a third line, representing the low-voltage electric supply system or any sensitive signal line.
The comparison of simulation and measurement of crosstalk from the high-power cables to a single line is shown in Figure 13 for common mode currents on the shielded high-voltage system.

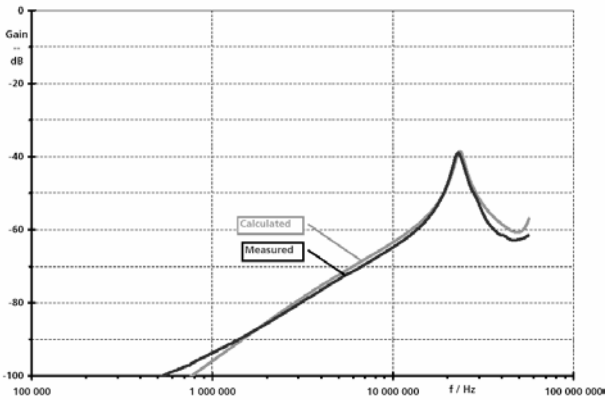

Figure 13: Measurement and Simulation of Crosstalk from Shielded Power Cable

The calculations match well with the measured data and therefore validate the model developed for the coupling path. Coupling values below -100 dB are ignored as measuring accuracy is not appropriate to resolve such high damping values. Above 30 MHz calculated coupling is little higher than the measured levels. The coupling level at the resonance frequency around 23 MHz is predicted exactly with the developed frequency domain model.

Based on the results of this work, the electromagnetic noise emitted by the electrical drive system converter can be quantified and possible measures can be developed. Since the two possible configurations with and without shielding can be compared, one of the main questions can be answered: whether or not shielded cables between the power converter and the power supply can replace the EMI filter. For both configurations, the remaining effort necessary for filtering can be determined and discussed in terms of cost, weight and space.

Coupling through the DC /DC-Converter

Differential-Mode Noise

Conducting research of the transmission of differential-mode noise is not necessary because the goal of the DC / DC converter is to switch the input voltage fast. By this means, noise levels intently generated are much higher than any noise levels in the system. So it can be assumed that appropriate filter measures to damp the differential-mode noise generated by the DC-DC-Converter are applied, which in turns also damp the transmitted noise below the verifiable limits. Here, the research has been focused on the common-mode noise only.

Common-Mode Noise

Without any additional filter measures, common-mode noise is damped in a DC/DC Converter only by the winding capacitance that occurs between primary and secondary winding of potential-free power supplies. Additional filter elements increase the damping effect of common-mode noise. Both characteristics can be measured with a suitable Gain-Phase-Analyzer.

To measure the common mode characteristics, measurements are conducted off-line. Measurements under no load conditions are appropriate if the following boundary conditions are taken into account:

1. In power supplies of small and medium power transmission, only one pole is switched. The common-mode noise then takes the path through the non-switched pole.

2. The switches under no load conditions are capacitors sized about 1nF. The coupling capacitance of the converter is around 100 pF. Compared to the coupling capacitance of the converter, the switches are considered as short circuits in order to model their behavior appropriate.

A measurement signal is given on both input poles of the converter related to the housing potential. Figure 14 shows the voltage between the output poles and the housing in dB, related to the voltage between the input poles and the housing of the converter.

Damping of common-mode noise is appropriate below 10 MHz. At higher frequencies poorly damped resonances occur which show damping of less than 10 dB. Together with the filter which is designed for this example, damping is increased to almost 50 dB over the whole frequency range.

With the DC-DC-Converter fulfilling the requirements regarding differential-mode noise and damping common-mode noise by 50 dB the decoupling of the High- and Low-Voltage Busses is considered being sufficient.

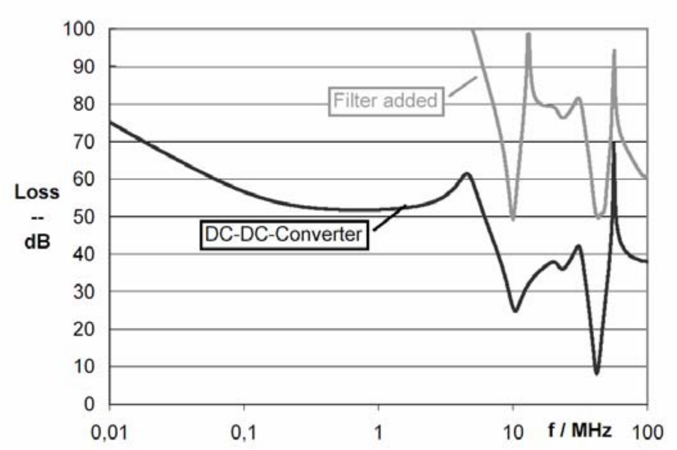

Figure 14: Damping effect of the DC / DC converter

EMC REQUIREMENTS FOR A HIGH-VOLTAGE BUS

Based on the determined model of the coupling path, the limits for the high-voltage bus can be derived. The underlying idea is that the noise caused in the low-voltage system must not exceed the limits for this system. Therefore, the noise on the low-voltage bus can be taken directly from the EMC requirements for automotive components.

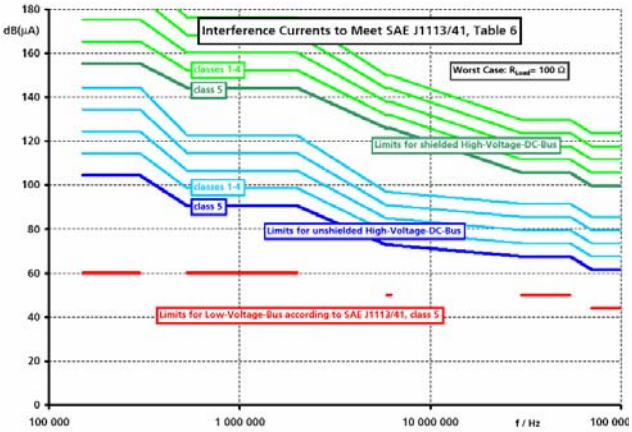

Figure 15: Limits for Interference Currents on the High-Voltage Bus to Meet Standards for Broadband Conducted Disturbances on Control/Signal Lines, Peak Values

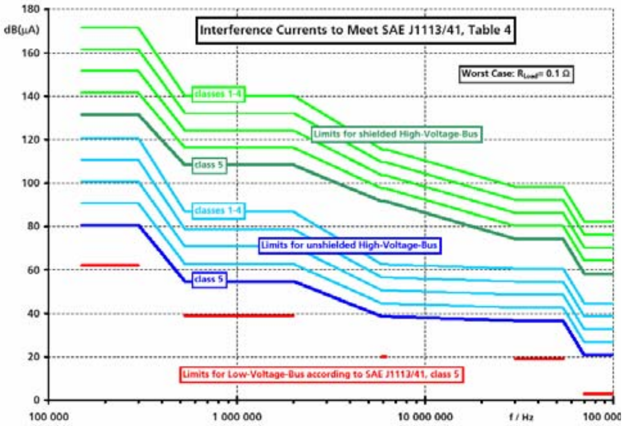

Figure 16: Limits for Interference Currents on the High-Voltage Bus to Meet Standards for Broadband Conducted Disturbances on Power Input Terminals, Peak Values

The low-voltage line is connected to the LISN on one side and to a low-voltage component on the other side. Impedance of the input terminal of the component is supposed to be small for worst-case inspection. In case of signal lines, input terminal impedance is highly ohmic, at least 100 Ω. Power input terminals are less ohmic, at least 0.1 Ω.

As maximum coupling occurs at resonance frequencies, the length of the cables has to be taken into account. In order to determine limits, the maximum coupling from cables of lengths from 0.5 m up to 2.2 m is calculated. The given values for current limits on power cables can be used for 70 mm^2 cables of lengths from 0.5 m up to 2.2 m.
 shows peak values of limits for interference currents on the shielded and the unshielded high-voltage bus in a way that the current limits are met on a closely placed signal line as defined in the standards [5], Table 6). In comparison, the lowest limits (class 5) defined in the standards for signal lines are also

pictured in . The limits on the high-voltage bus are pictured for all defined classes but the limits fulfilling class 5 requirements are emphasized. Limits on the unshielded high-voltage bus are 18 dB higher than standard limits. Interference currents on the shielded high-voltage bus can be another 37 dB higher than on the unshielded bus.

The interference current limits to fulfill the requirements concerning interference voltage at the measurement port of the LISN [5], Table 4) are shown in . In comparison, the lowest voltage limits (class 5) defined in the standards for power input terminals are also pictured converted to current limits on the low-voltage system according to . Again limits on the unshielded high-voltage bus are 18 dB higher than standard limits and limits for the shielded high-voltage bus can be another 37 dB higher than on the unshielded bus. Limits in are lower than limits in . These limits allow the discussion of shielding versus filtering effort in terms of costs, weight and space.

CONCLUSION

The authors of this paper have presented the EMC issues related to the integration of an electric drive system into a conventional passenger car. The components of the drive system have been analyzed being either noise source or part of the coupling path. Simulation models have been created for EMI prediction as well as for the development of optimized mitigations. The results of this investigation can be used to determine the acceptable noise levels on a high voltage bus of an electric drive system.

The simulation results have been confirmed by measurements using components of an electric drive designed for a passenger car.

With these results, shielding and filtering measures can be verified and costs of the system can be optimized. Further research has to be carried out to model all relevant configurations.

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